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Occurrence and measurement of salinity stratification in shallow groundwater in the Murrumbidgee Irrigation Area, south-eastern Australia

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Abstract

Capillary upflow from shallow groundwater is a significant contributor of soil salinisation in irrigated areas and is highly dependent on water table position and salinity. Lysimeters have traditionally been used to quantify capillary upflow from shallow water tables and the potential salinisation risk. However, water table position and salinity are usually controlled to remain constant in lysimeter studies, while short-term variations in these parameters may exist under surface irrigated agriculture. Consequently, the extrapolation of calculated crop water uptake and potential soil salinisation processes from lysimeter studies to field conditions may be misleading in selected cases. A multilevel sampler was designed to collect water samples at 20 cm intervals to investigate changes in water table position and salinity stratification of a shallow fluctuating water table under furrow irrigated fields. Water samples were taken from the upper 20 cm of the shallow groundwater (the water table zone, WTZ) as it rose and fell following irrigation events at three farms in the Murrumbidgee Irrigation Area, in south-western New South Wales, Australia. The water table was within 2 m of the ground surface at all sites and irrigation events resulted in large fluctuations in water table position over the irrigation season. Salinity stratification of the shallow groundwater was found to exist with low salinity water overlying more saline groundwater and a zone of variable

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salinity extending up to 2 m. The salinity generally increased with depth. In addition to changes in shallow groundwater salinity with depth, salinity fluctuated at specific depths over the irrigation season. The salinity of the WTZ also varied with changes in water table position. Following an irrigation event, a rising water table is associated with lower salinity at the WTZ. At each depth interval sampled, the salinity increased between water table rise and fall. The water table position and salinity are important determinants of salinity risks since they are the foundation for capillary upflow. Consequently, short-term variations in the position and salinity of shallow water tables under field conditions will affect capillary upflow and salt movement into the root zone. Therefore, where variations in these parameters exist at the field scale, detailed measurements should be taken to accurately predict crop water uptake and assess potential soil salinisation hazards.

Keywords: Salinity stratification; Irrigation salinity; Shallow groundwater

1. Introduction

Shallow water tables are a common feature of many irrigation areas due to high recharge rates and, frequently, reduced drainage rates. Once groundwater is in close proximity to the ground surface, capillary upflow results in the movement of water and salts towards the soil surface potentially leading to salt accumulation in the root zone. Soil salinisation above the water table is therefore affected by capillary upflow, groundwater position, groundwater salinity and soil and crop characteristics (Soppe and Ayars, 2003; Hutmacher et al., 1996; King et al., 1995; Prathapar et al., 1992; Prathapar and Meyer, 1992). Recharge from rainfall and irrigation will also affect soil salinisation and alter water table position and salinity depending on the salt stored in the soil profile and the quality and quantity of recharge water.

Due to the difficulty in measuring capillary upflow and water fluxes in the field, shallow groundwater environments have traditionally been investigated using lysimeters (Soppe and Ayars, 2003; Bethune and Batey, 2002; Slavich et al., 2002; Rogers, 2001; Hutmacher et al., 1996; Kruse et al., 1993; Prathapar and Meyer, 1992). Lysimeters are highly controlled environments in which water fluxes can be accurately monitored to determine crop water use and capillary upflow. Whilst the effect of different water table positions and salinities have been extensively examined, both of these parameters are usually kept constant by Mariotte bottle systems that attach to the lysimeters and act as a simulated water table (Soppe and Ayars, 2003; Hutmacher et al., 1996; Kang et al., 2001; King et al., 1995).

Lysimeter based research of shallow water tables emphasises the importance of considering not only the ability of a crop to use shallow groundwater, but also the resultant salt accumulation in the root zone, which is frequently highlighted as an adverse consequence of crop water uptake. Water table position and salinity were found to influence salt distribution in the soil profile across a number of studies (Soppe and Ayars, 2003; Ayars et al., 1999; Hutmacher et al., 1996; King et al., 1995; Kruse et al., 1993). Hutmacher et al. (1996) found that higher groundwater salinities (>20 dS/m) resulted in increased salinisation of soil deeper in the profile compared to treatments with less saline groundwater. They concluded that restricted shallow groundwater use under such saline conditions limited the amount of salt accumulating in the upper part of the soil profile.

Greater exploitation of the shallow groundwater in less saline treatments, however, transported more salt higher up into the profile, and coupled with minimal leaching in the growing season, resulted in greater salt accumulation in the profile. These findings have been replicated in other research (Kruse et al., 1993; King et al., 1995).

Whilst lysimeters offer the most precise experimental technique for determining capillary upflow from shallow groundwater and associated processes of salt accumulation and crop water use, it has been noted that lysimeters are artificial environments (Zhang et al., 1999). The experimentally controlled water tables in lysimeters will fluctuate with evapotranspiration and water supply from the Mariotte bottle system, however, fluctuations under field conditions of surface irrigation may be significantly greater. Consequently, there may be some difference between the capillary upflow calculated in lysimeters to those occurring in the field. Field based studies of capillary upflow from shallow water tables are rare, however, since calculations of capillary upflow and salt accumulation in the profile are difficult to measure in the field (Zhang et al., 1999).

In a field trial, Wallender et al. (1979) determined that groundwater contribution represented 59–70% of total season evapotranspiration in furrow irrigated cotton. Water table height was measured in five 3 m wells at weekly intervals and the groundwater salinity measured once over the experimental period. This sampling regime may be insufficient to accurately determine capillary upflow since these factors are highly variable under surface irrigation. In another field based experiment on furrow irrigated cotton, Ayars and Schoneman (1986) determined that 0–37% of crop water requirement could be met by shallow groundwater. The irrigation water had an average salinity of 0.2 dS/m and the groundwater 10 dS/m. The variation in percentage contribution varied between years, however, good agreement was consistently found between increased amounts of stored irrigation water and reduced groundwater use.

Past research into fluctuations in water table position and associated changes in salinity have largely been in response to long-term rainfall and climatic conditions rather than irrigation events. Intensive sampling of short-term fluctuations of the water table and the associated processes of solute movement and accumulation have received very little research attention, either at the field scale or using lysimeters. Rhoades and Loveday (1990) noted that crop responses are difficult to predict under conditions of shallow saline groundwater and good quality irrigation water due to changes in soil water quality over time and in different parts of the root zone. The rapid, short-term spatial and temporal changes occurring in the physical and chemical parameters of irrigated environments are frequently neglected since such studies require intensive sampling and long time frames (Cetin and Diker, 2003). High temporal and spatial variability in water table position of shallow aquifers was highlighted by Timms et al. (2001) as problematic in determining accurate trends of water table movement, however, dryland salinisation on the Liverpool Plains in north-western NSW was closely related to shallow groundwater dynamics and the salt-rich clay soils. Water level response was due to rainfall recharge. Salts appeared to be mobilised from clays by increased water fluxes, however the need for greater understanding of the short-term processes determining water and solute fluxes in clays was highlighted. Wang et al. (2002) found cyclic variations in soil salinity following saline irrigation of soybeans in drip and sprinkler plots. The soil salinity at 10 cm fluctuated between approximately 4–9 dS/m over the growing season.

Peak salinity values were found to correspond to the infiltration wetting front. It was suggested that the vertical movement of water would carry the soil salts down the profile, creating a pulse of high salinity water. However, similar patterns were not detected in furrow irrigated plots.

Variations in salinity with water table position may result in non-uniform distribution of salt with depth in shallow groundwater systems. Groundwater stratification has been reported in the Indus River Basin in Pakistan, where the percolation of irrigation water has formed a fresh shallow layer, varying in thickness between 3 and 150 m, over the underlying saline groundwater (Saeed et al., 2003; Asghar et al., 2002). The interface between the percolated irrigation water and the underlying groundwater is not static, responding to recharge and discharge mechanisms (Asghar et al., 2002). Kass et al. (2005) investigated the impact of irrigation on underlying groundwater (21–24 m) quality. The salinity and composition of the top 3–5 m of the saturated zone was found to be distinctly different to the composition of irrigation water, and was controlled by irrigation water composition and the processes occurring in the overlying unsaturated zone. The major chemical modifications occurring during the infiltration of the irrigation water suggest that a relatively complex relationship exists between the composition of the irrigation water and that of the underlying groundwater. The authors highlight the importance of the water table region as a sensitive indicator of the extent and dynamics of groundwater quality. Ronen et al. (1988) found chloride concentrations varied down a 2 m profile in Israel and determined these variations were not related to fluctuations in the water table (up to 18 cm). Chloride concentrations also varied with time over the experimental period of 7 months.

Soils underlain by shallow water tables have a high salinisation risk due to capillary upflow transporting salts into the root zone. Salinity stratification of shallow groundwater may minimise this risk. Surface irrigation events introduce large volumes of fresh water which infiltrate into the root zone over a relatively short period of time, followed by extended periods of drying and water extraction by the crop. The movement of fresher irrigation water through ‘preferred paths’ may be an important factor in this process. If the irrigation water applied is less saline than the underlying groundwater and bypass flow results in the rapid infiltration of this water to the top of the water table, stratification may result in fresh water overlying more saline deeper groundwater. Capillary upflow from a fresher layer of groundwater may introduce less salt into the root zone and encourage greater groundwater uptake by crops.

The objectives of this paper are to: (1) describe a technique to measure the stratification of shallow water tables in the field and (2) report and analyse water table fluctuation and stratification processes under surface-irrigated land in the MIA.

2. Materials and methods

2.1. Site

Trials were undertaken on three farms in the MIA, which is located in the Riverine Plain in the south-eastern part of the Murray-Darling Basin. The MIA is made up of a series of

Table 1
Site descriptions

Site	Year studied	Crop	Soil	Irrigation method	Amount/timing	Bed layout	Water table (m)
1a	2002/03	Maize	Self-mulching clay	Graded furrow	7–10 days	Raised bed	1.1
b	2003/04					2 rows/bed	
2	2003/04	Tomato	Transitional red brown earth	Graded furrow (alternate)	6 days	Raised bed 1 row/bed	1.8
3	2003/04	Pumpkin	Clay loam	Graded furrow	1 meg/irrigation	Raised bed 2 rows/bed	1.2

alluvial fans and floodplains interbedded with aeolian 'parna' deposits (Butler and Hutton, 1956). Local groundwater systems are contained within the Shepparton Formation and are underlain by the regional systems of the Renmark Group. The groundwater systems are layered with the most saline waters occurring in the upper-most aquifers (Brown and Stephenson, 1991).

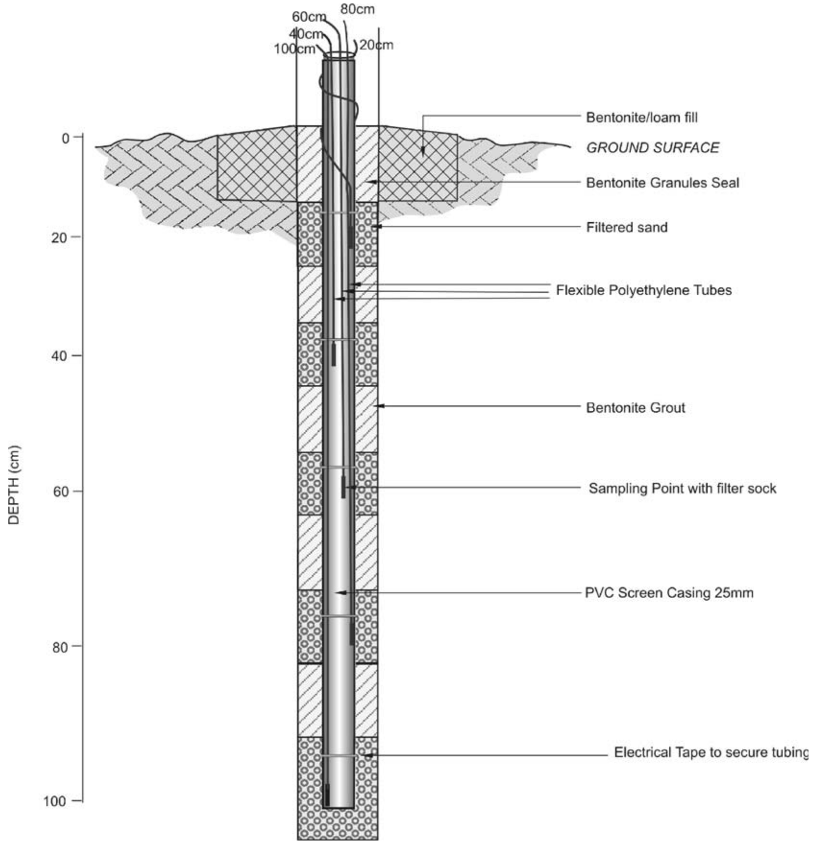


Fig. 1. Multilevel groundwater sampler.

The water table has risen steadily since irrigation began in 1913 and now lies within 2 m of the soil surface over a large area; however, recent dry years have decreased the water table height somewhat. Sites were selected to incorporate a variety of soil types, crops and to cover the range of water table positions and salinities in the area (Table 1). Particle size analysis showed all soils are dominated by clays, ranging from 43 to 65% with appreciable fine sand (21–45%).

The climate is classified as semi arid based on an aridity index that is a ratio of evapotranspiration (ET) to rainfall (R) (ET/R = 0.5–9.5), with essentially uniform rainfall throughout the year.

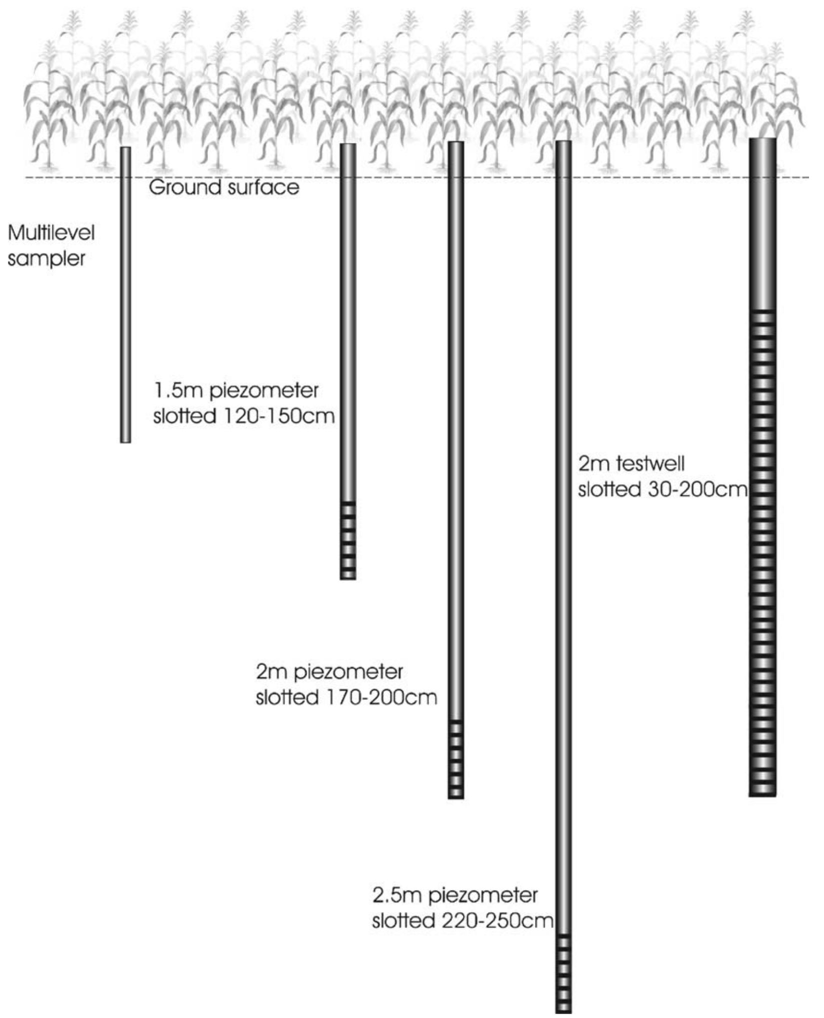


Fig. 2. Cross-section of experimental layout.

2.2. Experimental set-up

It was necessary to design a piezometer capable of sampling at different depths during water table rise and fall to examine changes in groundwater salinity at different water table positions. For this purpose, a multilevel sampler was designed (see Fig. 1). Multilayer samplers have previously been used to investigate chemical variations in the top section of static water tables in irrigated areas and aquifers influenced by anthropogenic factors (Kass et al., 2005; Ronen et al., 1988, 1986).

Due to the shallow nature of water tables in the area, multilevel samplers were installed to depths of between 1 and 2 m to determine vertical and temporal changes in shallow groundwater salinity as the water table fluctuated over the irrigation season. Each multilevel sampler consisted of small-diameter flexible polyethylene tubes (o.d. 5 mm) attached to a rigid polyvinyl chloride (PVC) pipe (o.d. 25 mm) using electrical tape. Field installation was performed manually using a dutch auger, creating a hole wider in diameter (50 mm) than that of the sampler (approximately 30 mm with attached tubing). The multilevel sampler was backfilled with clean, fine grained filter sand around the sampling points and bentonite in between the layers to avoid any contamination between sampling depths.

The multilevel samplers were installed in the middle of the bed in the case of Sites 1 and 3 and beside the plant row at Site 2. Installed occurred at Sites 1a and b following inter-row cultivation to avoid damage to the instrumentation. Installation at Sites 2 and 3 occurred in the first few weeks after emergence to avoid damage to the crop. Sampling of the water table was undertaken throughout the growing season until harvest. At Sites 1b and 3 a second multilevel sampler was installed approximately 2 m away from the original to ensure results were spatially consistent.

Where the water table was approximately a meter below the ground surface (sites 1 and 3), a series of three nested piezometers (1.5, 2.0 and 2.5 m) were installed to characterise the underlying groundwater (Fig. 2). The piezometers were constructed from rigid PVC pipe (o.d. 30 mm) and slotted for 300 mm from the base of the piezometer. Automatic water table loggers were also installed in testwells constructed from PVC stormwater pipe (o.d. 50 mm) and slotted the length of the well up to 300 mm from the ground surface. The nested piezometers and testwell were used to monitor water table fluctuations and determine the timing of sample collection. All additional instrumentation was placed in line with the multilevel sampler and as close to the middle of the bed as possible to avoid interference from the furrows.

Water samples were collected from the upper zone of shallow groundwater at 20 cm intervals as the water table rose and fell following an irrigation event (Fig. 3). Shallow groundwater samples could be extracted from a specific depth when the water table reached the sand layer in the packing around the sampler, ensuring the top 20 cm of the shallow groundwater (water table zone, WTZ) was consistently sampled. Water samples were extracted using a low-flow peristaltic pump. Electrical conductivity (EC) was measured in the field using a HANNA[1] conductivity probe. Irrigation water salinity was sampled at the head of the furrow and beside the instrumentation at each site for each irrigation event. Salinity values were consistent between locations. Water samples were also analysed for pH, major ion and nutrient concentration (data not presented).

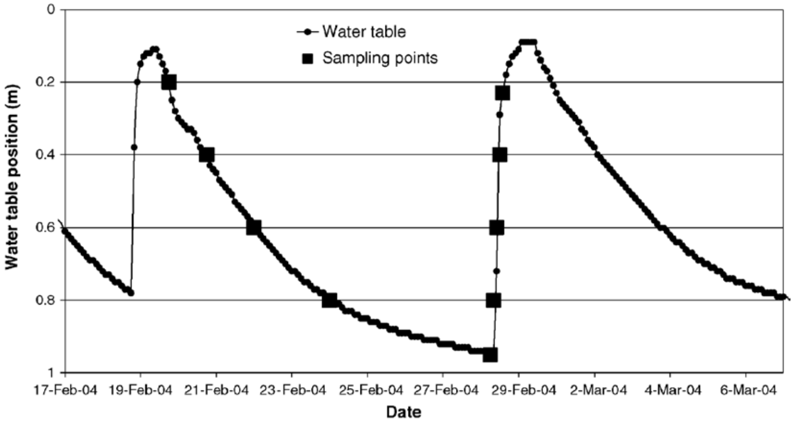


Fig. 3. Sampling points during water table rise and fall.

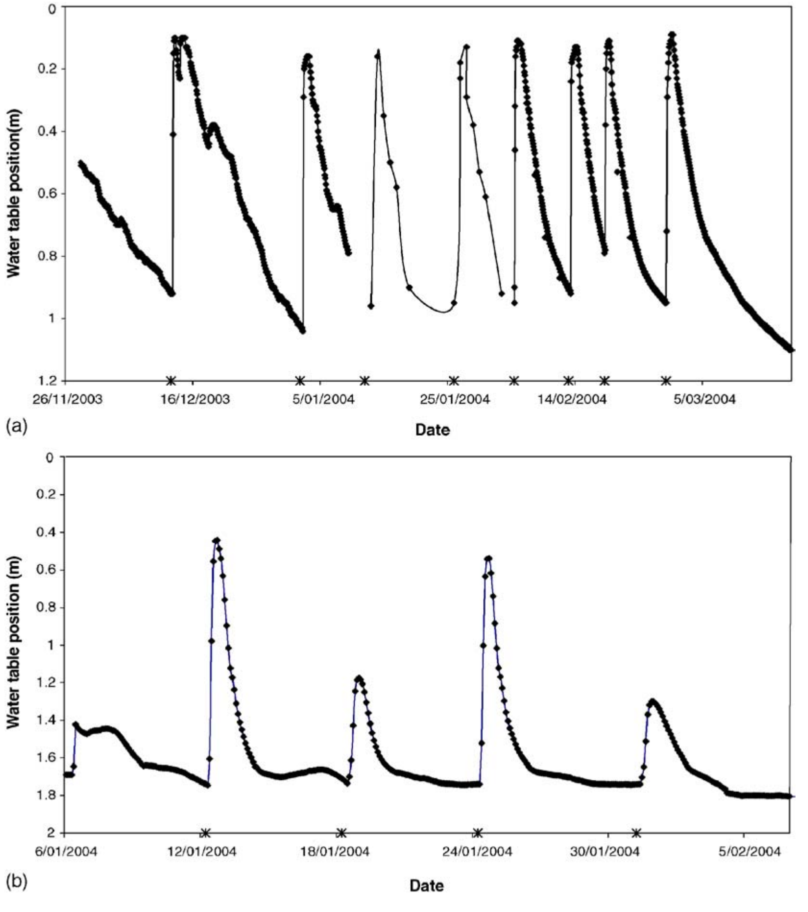
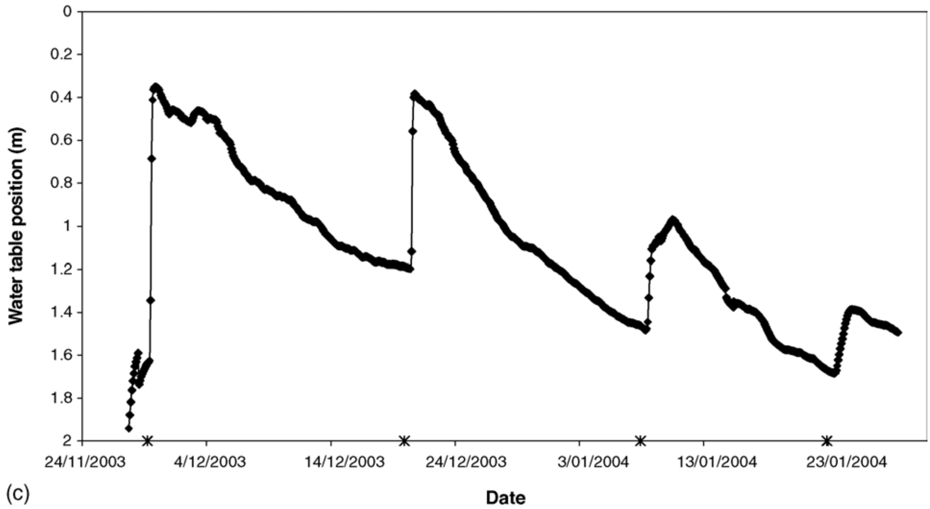


Fig. 4. Water table depths measured in testwells under (a) Site 1b, (b) Site 2 and (c) Site 3. (*) Irrigation event.



(c)

Fig. 4. (*Continued*).

3. Results and discussion

Automatically logged data collected from the testwells of all three sites shows the range of water table fluctuations under furrow irrigation (Fig. 4). Water table rise is rapid across all sites, ranging from approximately 6–12 h. This would indicate a large fraction of the flow may be occurring via macropores (bypass flow). Cracks were observed in the surface soil at all sites. Water table fluctuations vary in magnitude across the three sites, due to site specific irrigation management practices and soil characteristics. The water table fluctuation pattern at Site 1b is highly consistent, fluctuating between 1 m and the ground surface over each irrigation cycle. The amount of irrigation water applied at this site was found to vary considerably between irrigation events. The water table under Site 2 rises to within 0.4 m of the ground surface following an irrigation event, however, when the depth of the furrow is taken into account, the water table is effectively at ground surface. The water table rises and falls more rapidly following an irrigation event at Site 2 than elsewhere. Every second furrow is irrigated at Site 2 and the rows alternate between irrigations, which may explain the consistent differences in the magnitude of water table fluctuations between irrigation events. The water table fluctuations at Site 3 gradually declined throughout the season; with each irrigation event the water table rise was less and water table decline greater. This effect is often seen as plant root systems and canopies develop through the season, thus using more of the stored soil water between irrigations resulting in more soil water storage and less water reaching the water table. There was minimal rainfall over the irrigation season and all accessions to the water table resulted from irrigation events.

The salinity of the water table varies with depth across all sites (Fig. 5). Salinity generally increases with depth, as is common in irrigated areas where salts in the topsoil have been leached by irrigation (Rhoades, 1972). This stratification of the shallow groundwater persists throughout the irrigation season, creating a zone of variable salinity up to 1–2 m deep. Variations in salinity at each depth are timed with the irrigation cycle. Ronen et al. (1988) also found that recharge from rainfall and irrigation resulted in discrete water layers of different chemical composition down the top 30 m of the water table. A decrease in salinity occurs during and immediately after an irrigation event (which can take up to 12 h), followed by an increase during the drying phase. During this drying phase in the days following an irrigation event, crop water uptake from the soil would induce

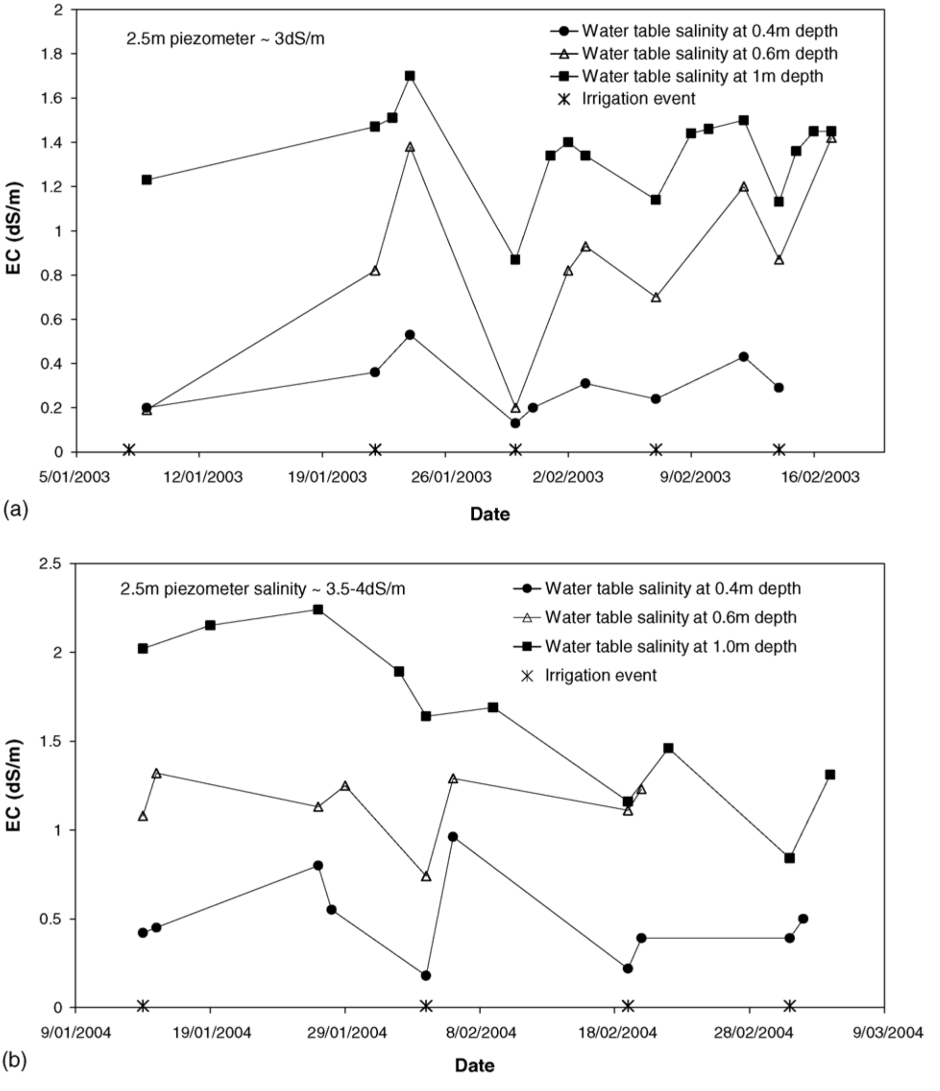
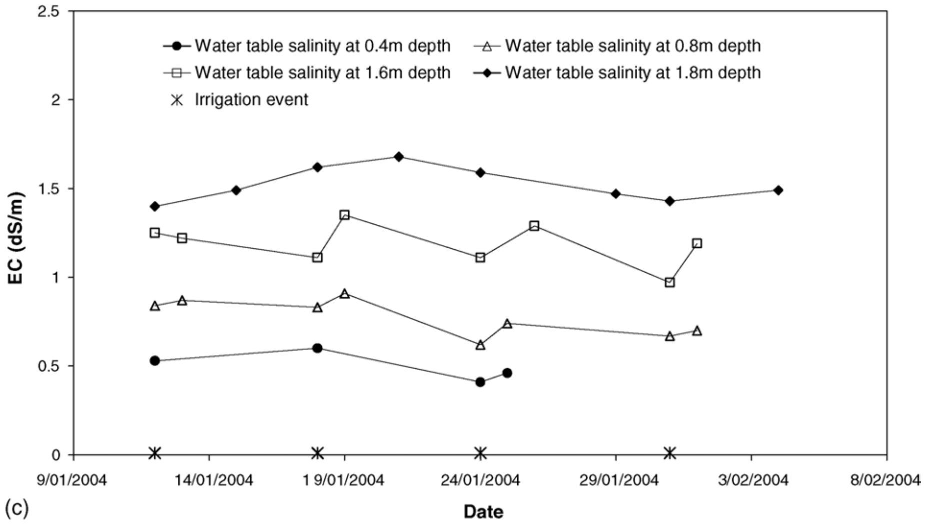


Fig. 5. Groundwater salinity variations with depth under (a) Site 1a, (b) Site1b (c) Site 2 and (d) Site 3. (*) Irrigation event.



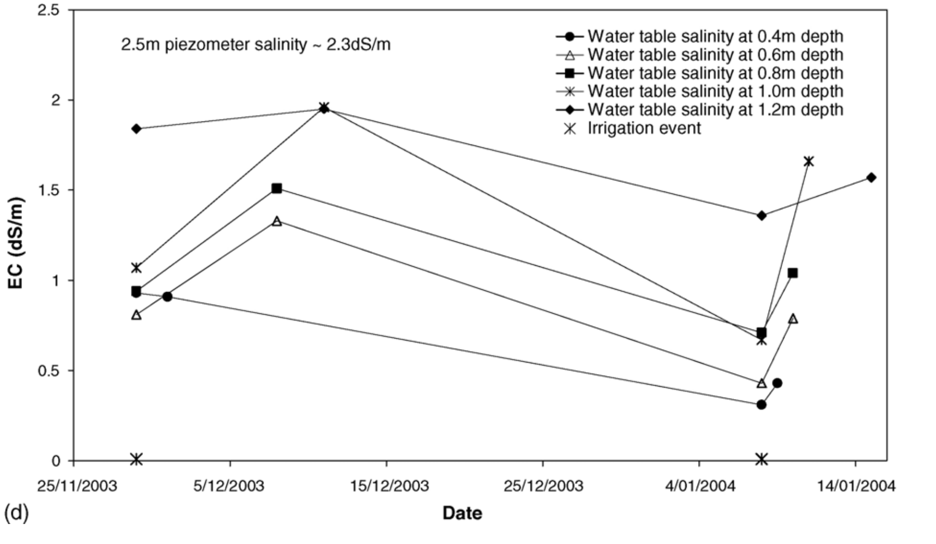


Fig. 5. (*Continued*).

capillary upflow from the shallow groundwater, removing fresh water from the profile and leaving the salts behind resulting in the increase in salinity. Simultaneously, drainage of the fresher irrigation water from the macropores to the groundwater system as the water table falls may transport some salts with the vertical movement of the water table, creating a salinity bulge at the top of the water table.

The results presented in Figs. 4 and 5 indicate that: (1) water tables fluctuate greatly under surface irrigation across a variety of field conditions; (2) determining shallow groundwater salinity based on measurements from a single depth may not provide an accurate description of salinity down the water column in irrigated systems. Calculations of capillary rise and salt accumulation from different depths in the water table and at different times may result in different conclusions of the soil salinisation risk and crop water uptake rates.

The top of the water table is a dynamic zone of interaction between the groundwater, soil water, and the infiltrating irrigation water. Processes occurring in this zone, such as mixing, solute transport, water interactions with the soil matrix and fluctuations in the water table may result in salinity variations over short time periods. Changes in salinity and water table position (measured in the deeper piezometers and testwells) in the WTZ are illustrated in Fig. 6. Rising groundwater consistently corresponds to a decrease in salinity in the WTZ. As the water table falls, salinity steadily increases. Large fluctuations in salinity are apparent at all sites over changes of up to 2 m in water table position and persist throughout the growing season. Clearly, these variations in salinity cannot be explained by changes in

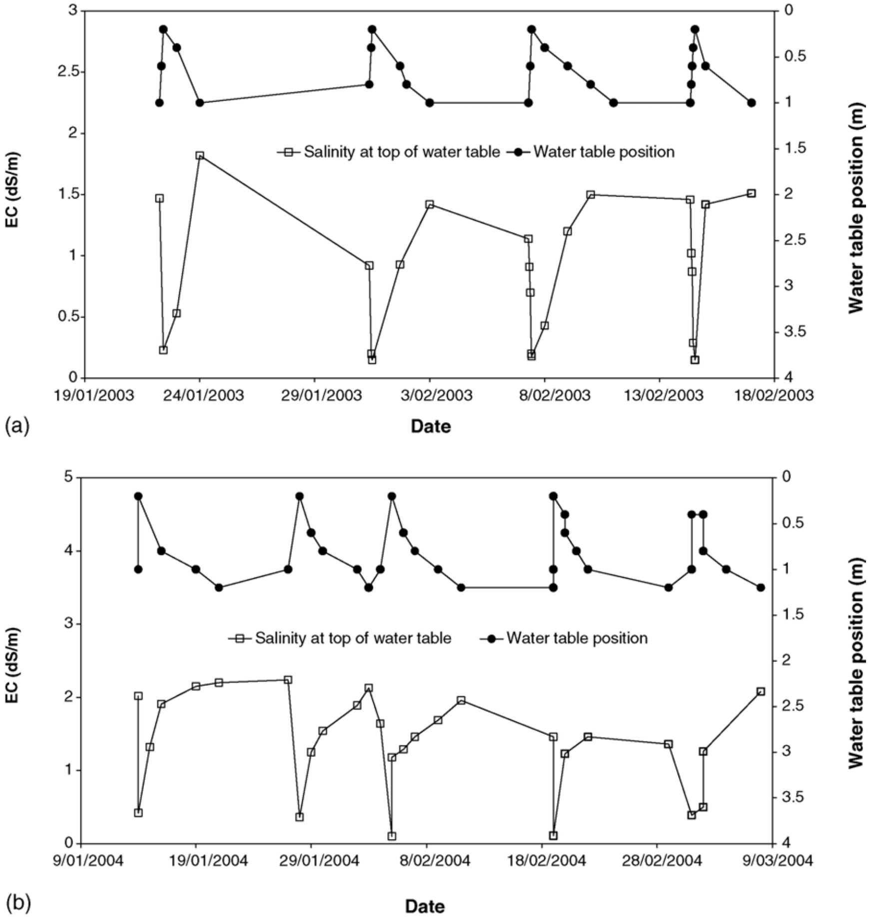
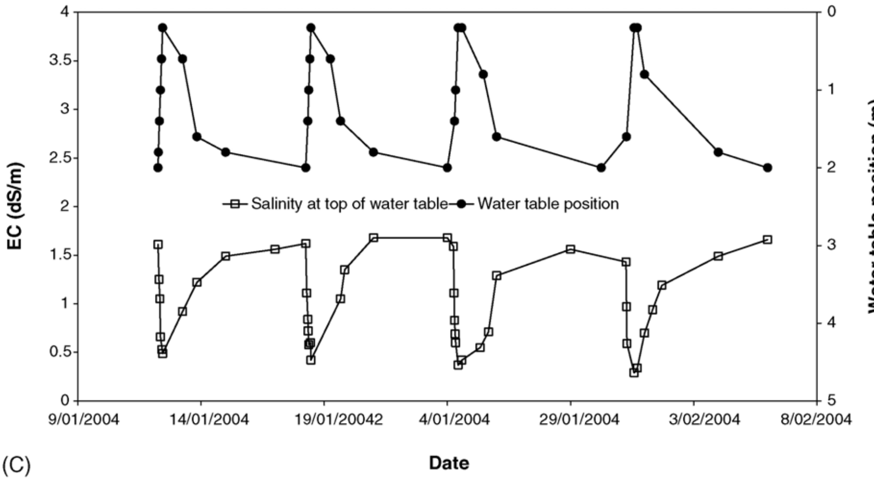


Fig. 6. Salinity variations at the WTZ for (a) Site 1a, (b) Site1b, (c) Site 2 and (d) Site 3.



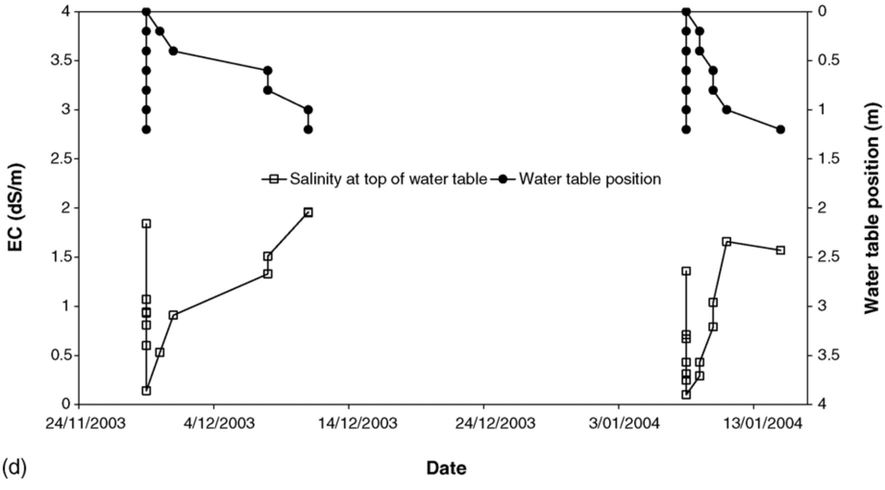


Fig. 6. (*Continued*).

the soil matrix over such short time intervals. These results are consistent with the cyclic pattern of soil water salinity following irrigation events found by Wang et al. (2002).

The salinity of the WTZ displays a hysteresis pattern as it rises and falls following a single irrigation event (Fig. 7). Salinity generally decreases with each 20 cm sampling interval during water table rise. When the water table height peaks, the salinity of the water in the uppermost operational sample point is very similar to that of the irrigation water. Water table fall corresponds to an increase in salinity relative to water table rise at each depth. Evapotranspiration from the soil profile and/or the dissolution of highly soluble salts while the profile is saturated may be causing this salinity increase. Changes in salinity of the 1.5–2.5 m nested piezometers is minimal over this period (data not presented).

When the WTZ is relatively low in salt (when it is very shallow immediately following an irrigation event) capillary upflow will result in less salt accumulation in the profile and crop water uptake of this groundwater is unlikely to adversely affect the crop. However, the water table remains at its lowest salinity for only 6–24 h across the different sites, after which the water table will have fallen and the salinity increased. Previous research has found that crops will largely ignore the more saline groundwater, preferentially taking up the fresher irrigation and rainfall water stored in the soil profile (Zhang et al., 1999). The

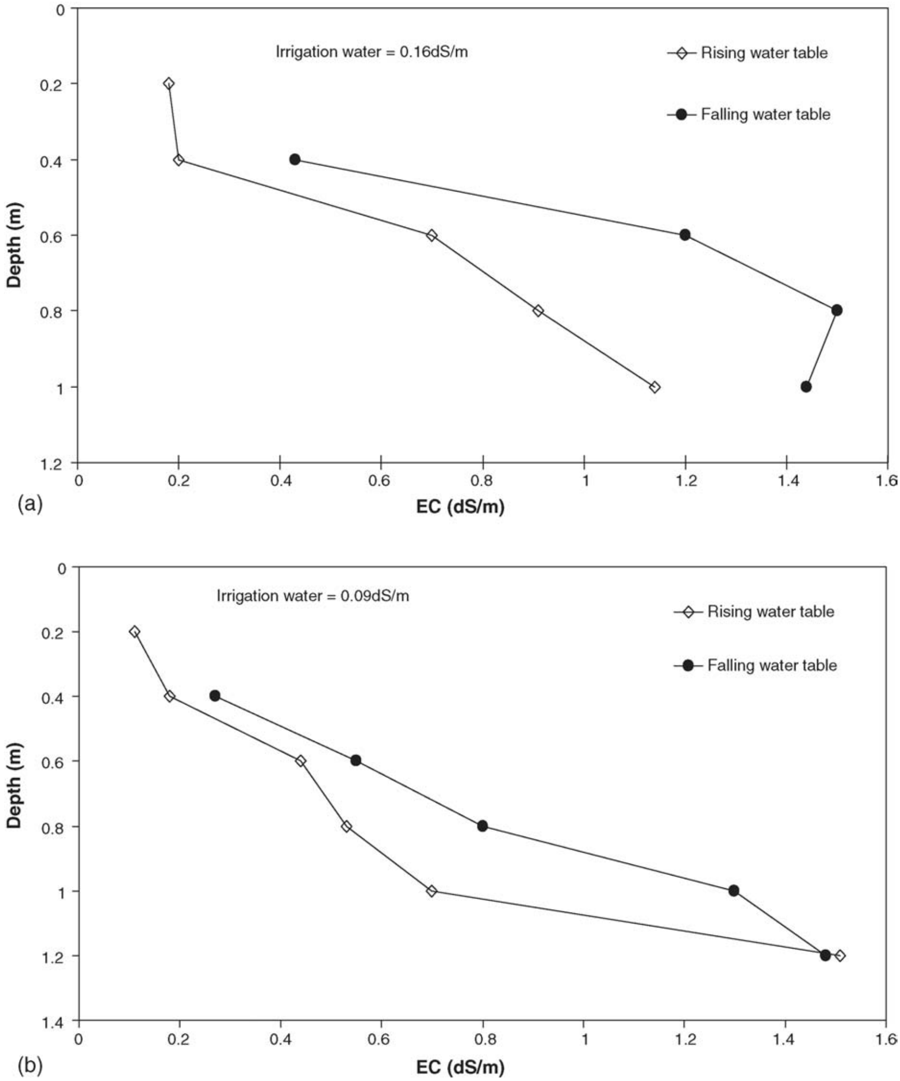


Fig. 7. Water table salinity under (a) Site 1a, (b) Site1b, (c) Site 2 and (d) Site 3 over changes in water table position after an irrigation event.

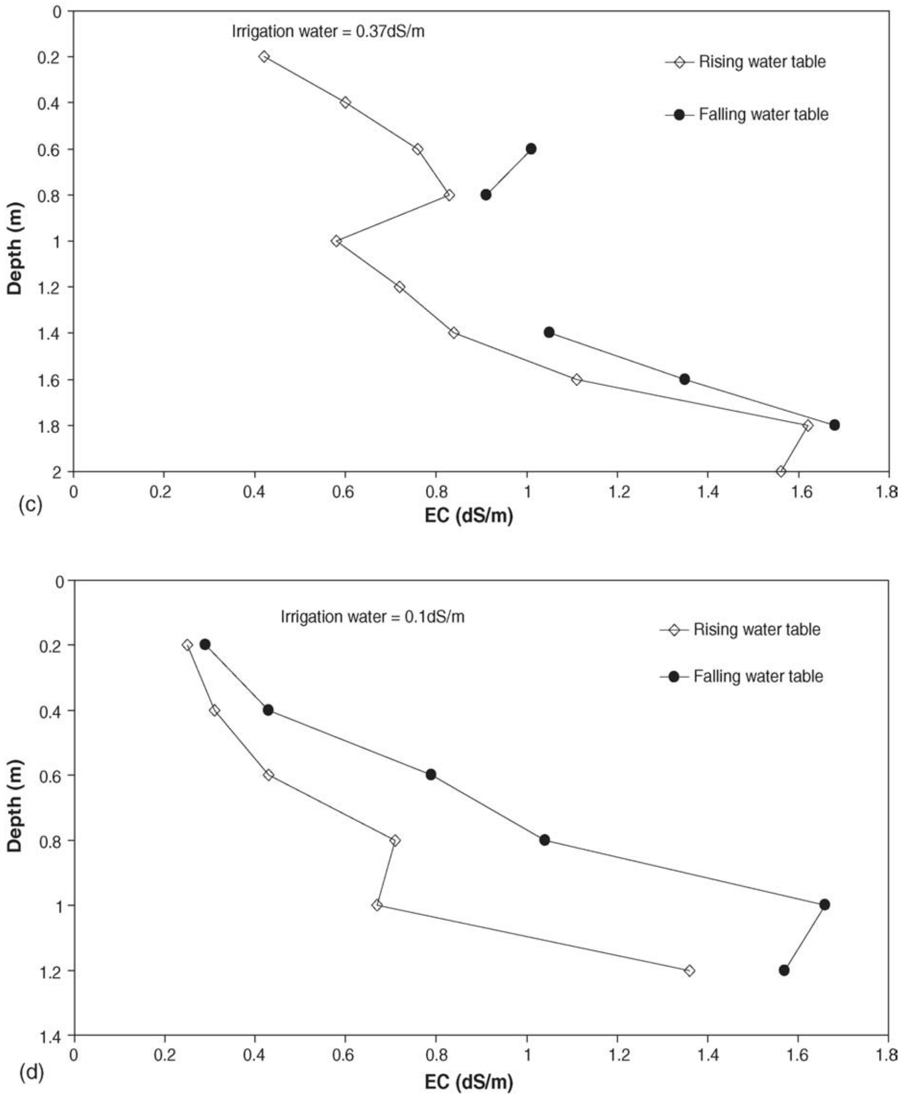


Fig. 7. (*Continued*).

timing of crop water uptake therefore becomes a factor. Since deeper water tables can correspond to a general decrease in groundwater uptake, a faster rate of water table decline and frequent irrigations may result in smaller increases in salinity between water table rise and fall (Fig. 7c). This may be due to less capillary upflow and reduced salt accumulation as the crop preferentially uptakes water stored in the soil. If there is a large increase in salinity as the water table falls (Fig. 7a) and the profile dries out considerably, greater crop water uptake of the shallow groundwater via capillary upflow has the potential to accumulate salts in the root zone. Salinity fluctuations at the top of the water table may therefore serve to either increase or decrease the potential for salinisation of the upper soil profile, depending on site specific characteristics.

4. Conclusions

A multilevel sampler was designed to sample the upper 20 cm of the WTZ as it rose and fell following an irrigation event. This enabled intensive sampling of short-term temporal and vertical variations in water table position and salinity of shallow groundwater under field conditions. Irrigation events caused large fluctuations in water table position over the growing season. These changes in the position of the water table were found to correspond to fluctuations in salinity at specific depths down the water column and in the WTZ. These findings are consistent with the few other studies that have examined cyclic changes in volumetric soil water content and salinity in irrigated areas, suggesting the results are not site-specific to the MIA. Changes in the salinity in the upper surface of the water table may have direct consequences for capillary upflow and salt accumulation in the soil profile.

Shallow groundwater stratification was evident at all sites, creating a zone of variable salinity that responded to irrigation events. Infiltration of fresher irrigation water occurred rapidly following an irrigation event, suggesting bypass flow may be important in rapidly transporting the irrigation water to the top of the water table, where it forms a fresher layer over the more saline groundwater.

The results presented indicate the importance of taking detailed time and depth measurements of shallow groundwater salinity under fluctuating water table conditions to assess crop water uptake and salinisation rates. Variations in salinity of the WTZ indicates that the rates of capillary upflow and subsequent soil salinisation determined by lysimeter studies may not be accurately extrapolated to all field conditions if limited measurements of the temporal variations in water table position and salinity are made.

Optimising the application of irrigation water into the system so sufficient water is supplied to the crop for maximum yield while reducing deep drainage to the groundwater may reduce water table fluctuations and variations in salinity in the WTZ. This would improve the accuracy of calculations of capillary upflow and soil salinisation rates under surface irrigated areas with shallow water tables. These results may also have implications for the use of saline irrigation waters as fresh water resources decline. Capillary upflow from a stratified water table, with a fresher upper layer resulting from the infiltration of irrigation water, would transport less salt into the root zone and increase the potential for crop water use of shallow groundwater. This process is only likely to continue as long as good quality irrigation water is used.

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